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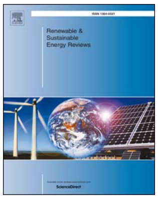

Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization

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ABSTRACT

In this paper we present results of a global resource assessment for geothermal energy within deep aquifers for direct heat utilization. Greenhouse heating, spatial heating, and spatial cooling are considered in this assessment. We derive subsurface temperatures from geophysical data and apply a volumetric heat-in-place method to improve current global geothermal resource base estimates for direct heat applications. The amount of thermal energy stored within aquifers depends on the Earth's heat flow, aquifer volume, and thermal properties. We assess the thermal energy available by estimating subsurface temperatures up to a depth of three kilometer depending on aquifer thickness. The distribution of geothermal resources is displayed in a series of maps and the depth of the minimum production temperature is used as an indicator of performance and technical feasibility. Suitable aquifers underlay 16% of the Earth's land surface and store an estimated $4{\cdot}10^5$ to $5{\cdot}10^6$ EJ that could theoretically be used for direct heat applications. Even with a conservative recovery factor of 1% and an assumed lifetime of 30 years, the annual recoverable geothermal energy is in the same order as the world final energy consumption of 363.5 EJ yr^{-1}. Although the amount of geothermal energy stored in aquifers is vast, geothermal direct heat applications are currently underdeveloped with less than one thousandth of their technical potential used.

1. Introduction

1.1. Background

Geothermal energy is heat that is stored in the subsurface and is a renewable resource that can be sustainably exploited. Humans have had a long history of using geothermal energy for heating, cooking, and bathing [1,2]. In 1904, in the Lardarello area in Tuscany, Italy, the beginning of a new geothermal era was marked by the first successful attempt to power a light bulb with electricity converted from geothermal heat (e.g. [2,3]). Today, electricity forms an essential part of modern life, but it is often overlooked that heat production accounts for more than half of the world final energy consumption [4]. Three quarters of this heat demand is currently met by fossil fuels [4], causing a significant impact on climate and environment [5].

1.2. Rationale and structure of the review

The key objective of this paper is to give an overview of low-enthalpy (< 150 °C) geothermal heat available in sedimentary aquifers suitable for direct utilization. An overview of the literature is given in Section 2, where we discuss geothermal energy in sedimentary aquifers, geothermal potential, production, installed capacity, and resource assessments. In Section 3, we present our global assessment of the geothermal resource base for direct heat. To quantify technical and theoretical potential, we apply a volumetric heat-in-place method. We explain how aquifer volume is derived and how associated subsurface temperatures are calculated using global geological and geophysical data sets. We estimate the geothermal potential for generalized direct heat and for common applications including greenhouse heating, spatial heating, and spatial cooling. We present our results in a series of maps that are made available online via a webGIS viewer: http://

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thermogis.nl/worldviewer. We discuss our results in Section 3.3, before we arrive to the main conclusions in Section 4.

2. Literature review

2.1. Geothermal systems in deep aquifers

Deep (> 100 m) geothermal aquifers are permeable layers of fluid-bearing rocks. Part of the heat that flows from the Earth's internals to its surface is stored in these aquifers and can be used directly for heating and cooling. When subsurface temperatures are sufficiently high, the heat can also be used to generate electricity. Apart from elevated temperatures in the subsurface, geothermal aquifers require high permeability to sustain flow rates that allow efficient transport of warm water from the aquifer to the surface. Sufficient permeability can occur naturally or it can be enhanced by stimulating the aquifer. Breede et al. [6], Olasolo et al. [7] and Lu [8] provide comprehensive reviews of existing enhanced geothermal systems including reservoir stimulation techniques that have been applied.

Similar to other deep subsurface activities that change temperature and pressure conditions in and around a reservoir, there is a small risk that geothermal activities cause mechanical failure of rocks and faults that could lead to seismicity [9]. To maintain public support for geothermal energy projects it is vital to prevent and minimize induced seismicity. Safe drilling, stimulation, and plant operation require sufficient understanding of subsurface structures and stress regime [10]. Gaucher et al. [11] review approaches to forecast induced seismicity, especially relevant for geothermal projects where faults are the main target for permeability or where reservoir stimulation is used to increase permeability.

Typical geothermal systems for direct heat consist of two or more wells: hot water is produced by production wells, while injection wells are used to re-inject the water after heat has been extracted. Re-injection is applied to preserve aquifer pressure allowing sustainable production and to prevent environmental contamination at the surface from geothermal fluids [12,13]. The cold water front created at the end of the re-injection well slowly migrates to the area of the production well, which eventually leads to thermal break-through. This severely reduces the efficiency of the geothermal system and marks the end of its lifetime (e.g. [14]). For doublet lifetime, it is important to consider well spacing [15] and the anisotropy of aquifer permeability [16]. The well-layout of most systems is designed to produce energy efficiently for a period of at least 30 years. Geothermal systems have been producing from the Dogger limestone aquifers in the Paris basin in France since the 1970's, which proves that lifetimes of 30 years or more are feasible [17]. Axelsson [18] lists other examples of sustained geothermal production, including a low-enthalpy system in Iceland that has been operational since the 1930's.

Lifetimes of geothermal systems can be extended up to 100 years by drilling new production and injection wells [19,20] or by optimizing production to a more sustainable rate (e.g. [21]). Compared to fossil fuel-based energy systems, geothermal energy systems are considered renewable since the time it takes to replenish 95% of the extracted heat is in the same order as the lifetime of the system [22]. Apart from technical and economical indicators, sustainability of geothermal energy can be assessed in a broader way, taking into account impact on environment and society [23]. Life cycle assessments show that geothermal energy plants have a significantly lower environmental footprint than fossil fuel-based plants [24–26] and that they are competitive with other forms of renewable energy [27].

2.2. Geothermal potential, production and installed capacity

In 2016, installed geothermal capacity for direct heat was 20.6 GW (equivalent electric power) [28,29], while installed geothermal capacity for electricity generation was 13.5 GW [30,31,29]. To date, the contribution of geothermal energy systems to the total energy mix has been limited: 0.15% or 0.565 EJ yr^{-1} of the world final energy consumption in 2015 (363.5 EJ yr^{-1}) [31,28,29]. Approximately 50% (0.286 EJ yr^{-1} excluding ground source heat pumps) is used for direct heat applications [28,29]. This accounts for less than 1% of the lower limit of the global geothermal resource base for direct heat, estimated by Stefansson [32] to be 32 EJ yr^{-1}.

By 2050, the International Energy Agency (IEA) [33] estimate geothermal production to be 5.8 EJ yr^{-1} for heat (3.9% of projected world final energy for heat) and 1400 TW h yr^{-1} for electricity (3.5% of projected world electricity production). In total, this production could avoid emission of almost 900 Mt yr^{-1} of CO_2[34,33]. Goldstein et al. [35] project a 27-fold increase of current geothermal heat production to 7.8 EJ yr^{-1} in 2050.

One of the main causes for the large mismatch between potential estimates and developed geothermal resources has to be sought in high up-front costs for drilling wells and associated financial risks related to geological uncertainties (e.g. [36,37]). During the exploration phase of a geothermal project, significant investments are required to de-risk prospects and to investigate their technical and economic feasibility. Drilling costs of a geothermal exploration well can easily comprise 15% of the total capital costs (CAPEX) [33,38].

Geological uncertainties and financial risks make it difficult for project developers to raise capital and to obtain insurance contracts [4]. Decentralized production of geothermal heat and the lack of uniformity among geothermal projects complicate governmental support policies to remove financial barriers (e.g. tax incentives and feed-in-tariffs for renewable energy or guarantee schemes for geothermal projects [39]) and non-financial barriers (e.g. adjusting regulation and legislation) (e.g [40,41]).

2.3. Geothermal resource assessments

Soaring prices of fossil fuels caused by the oil-crises of 1973 and 1979 stimulated research to quantify the potential of alternative energy sources including geothermal energy. The United States Geological Survey (USGS) developed a volumetric heat-in-place method [42,43], which has been used to estimate geothermal resources for global and regional and assessments (e.g. [32,44–46]). For this method, the area or region below the Earth's surface is divided into separate volumes. For each volume, the thermal energy in place (heat in place) is estimated based on measured or modelled subsurface temperatures.

Estimating the heat in place is straightforward, but it is more difficult to delimit the share that is technically producible. To direct this issue, it is common to apply an average value for the recovery factor to obtain the technical potential (e.g. [47]). However, little data are available on actual recovery factors, making it hard to assess whether a chosen recovery factor is realistic and appropriate for resource assessments of individual basins or entire regions [48]. More realistic recovery factors are used when data on location-specific aquifer permeability and temperature are available. For areas without any prior information or for global-scale assessments, a low recovery factor of is more appropriate [43,48]. A conservative recovery factor may lead to significant local underestimations, especially for well-explored and developed geo-ther-mal areas [43,48]. These are likely compensated by overestimation of the geothermal potential in parts of the world that have not yet been explored for geo-resources.

One of the main challenges for all resource assessments is uncertainty quantification, especially when dealing with geological data. Volumetric resource assessments are therefore often combined with probabilistic methods like the Monte-Carlo method (e.g. [36,49]). Multiple model runs yield a probability distribution of the potential, by allowing variation in parameters. It is crucial not to be overly restrictive with the ranges of allowed parameter variation and to include non-likely scenarios, since not all parameters will follow a Gaussian distribution [48,50]. Uncertainty quantification for a global geothermal